Development and Integration of Predictive Models for Manufacturing and Structural Performance of Carbon Fiber Composites for Automotive Applications

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General Motors

2017 Annual Merit Review

June 7, 2017

Project ID: LM117

Overview

Timeline

- Project Start Date: May 1, 2015
- Project End Date: April 30, 2019
- Percent Complete: 45 %

Budget

- Total project funding
  - DOE Share: $6,000,00
  - Contractor Share: $2,571,253
- Funding received in FY16 :
  - DOE Share: $1,481,318
  - Contractor Share: $634,851
- Funding for FY17:
  - DOE share: $1,726,896
  - Contractor share: $740,099

Barriers

A. ***Manufacturing Technology:*** Stochastic manufacturing simulation tools to predict the outcome within 15% of experimental results to reduce cost.

B. ***Performance Technology:*** Stochastic structural performance simulation to predict the outcome within 15% of experimental results to optimize design.

C. ***Integrated Technology:*** Integrative manufacturing and structural performance simulation tool that can be used in upfront design to deliver the required assembly performance without any trial and error.

Participants

General Motors
Continental Structural Plastics (CSP)
ESI Group, NA
Altair
University of Southern California

Relevance

Predictive Integrated Modeling Tools

- Primary deliverable: An ICME model capable of predicting stochastic manufacturing and structural performance of carbon fiber (CF) composites.
  - Reduce the cost of manufacturing of CF reinforced automotive components by eliminating trial and error through improved manufacturing simulations.
  - Design, optimize and validate the CF automotive structures in a virtual design space through improved performance modeling.
  - Reduce the lead time and cost to design and implement large scale structural automotive composites.
  - Enable the usage of CF composites for significant light-weighting of automobiles and thus improve fuel economy, and lower emissions, which will reduce greenhouse gas emissions.

Cost Barrier

- Will demonstrate the ability to manufacture the automotive CF composites at no more than **$4.32** cost per pound weight saved to address the DOE 2030 targets.

Performance Barrier

- Will demonstrate the viability of CF composites to meet vehicle performance requirements while reducing vehicle assembly weight **(35% lighter)** compared to a current steel design.

Relevance

Steps in implementing CF in automobiles

Current

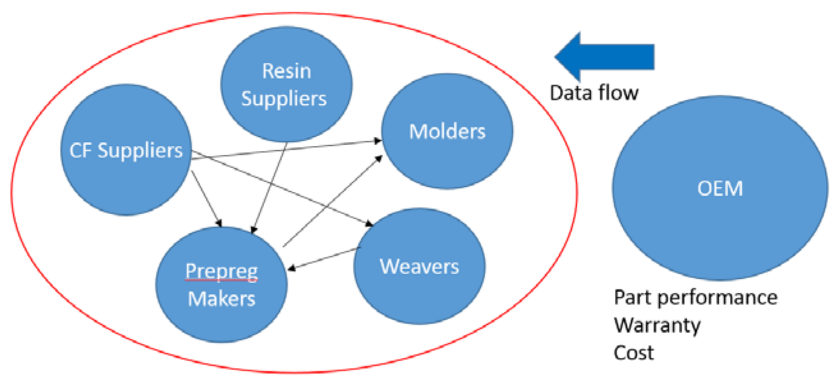
- Design.
- Selection of manufacturing process.
- Manufacturing feasibility.
- Prototype build and learn.
- Modify design and manufacturing process, if needed.
- Improve prototype build and make part.
- Extrapolate to high volume manufacturing.
- Build the part, iterate to get good quality.
- Evaluate the performance and compare with requirements.
- If failure occurs, redesign the part.

Future

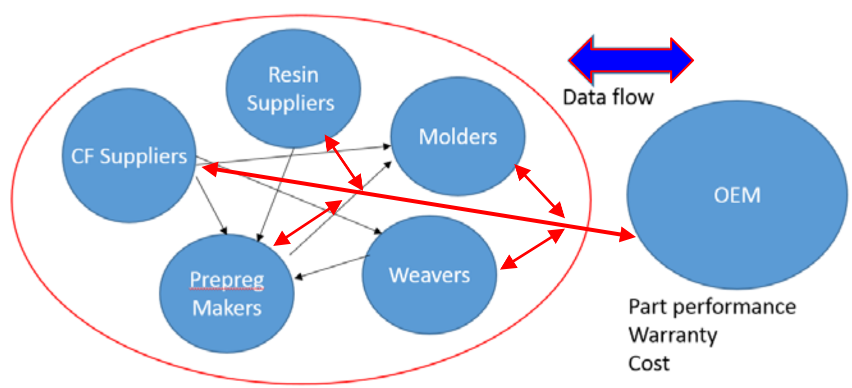
- Design.
- Virtual manufacturing simulation and improve the design for optimizing the cost.
- Include manufacturing outcome in performance simulation and further optimize the design to meet the requirements.
- Build tools, manufacture parts and check the performance

Work flow between OEM and Suppliers

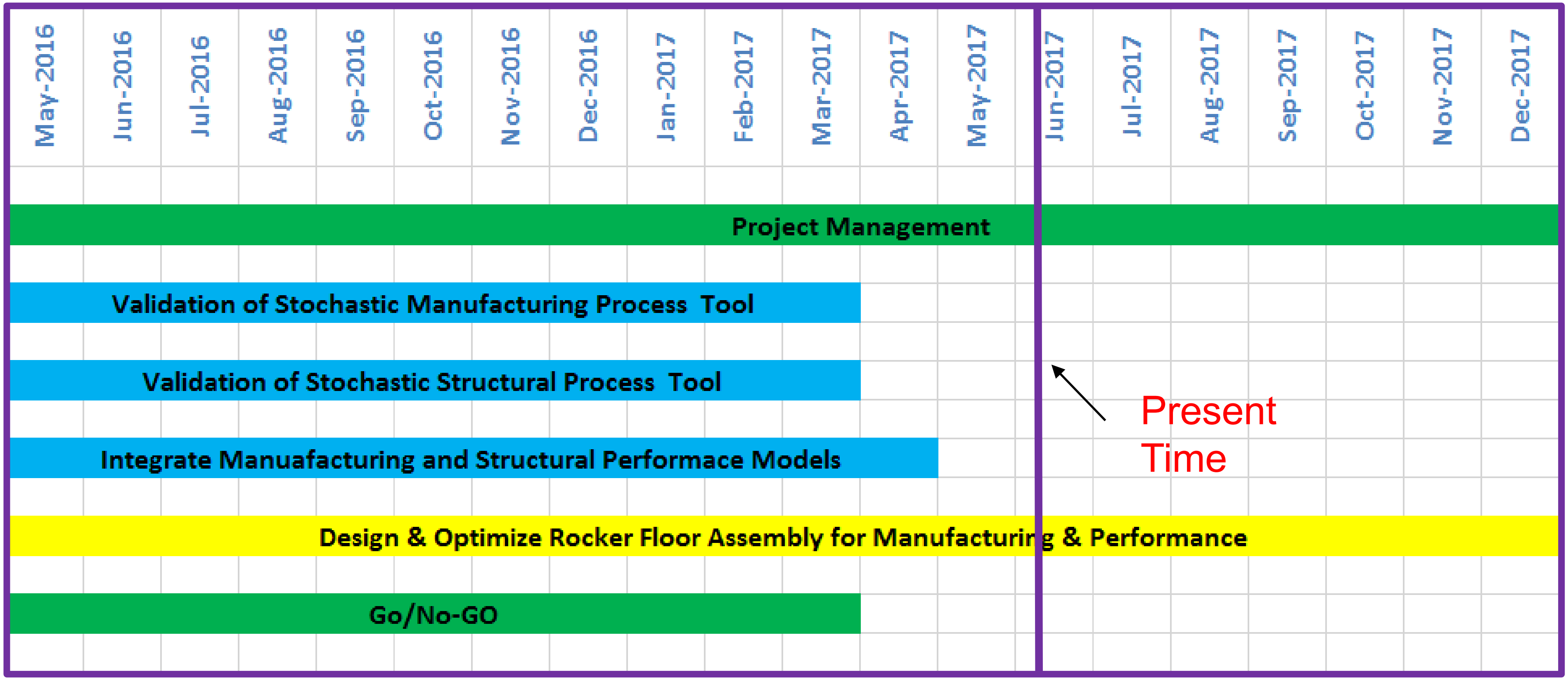
Current



Future



Milestones



All milestones for year 2017 are complete.
Go/No-Go decision was also complete.

Approach/Strategy

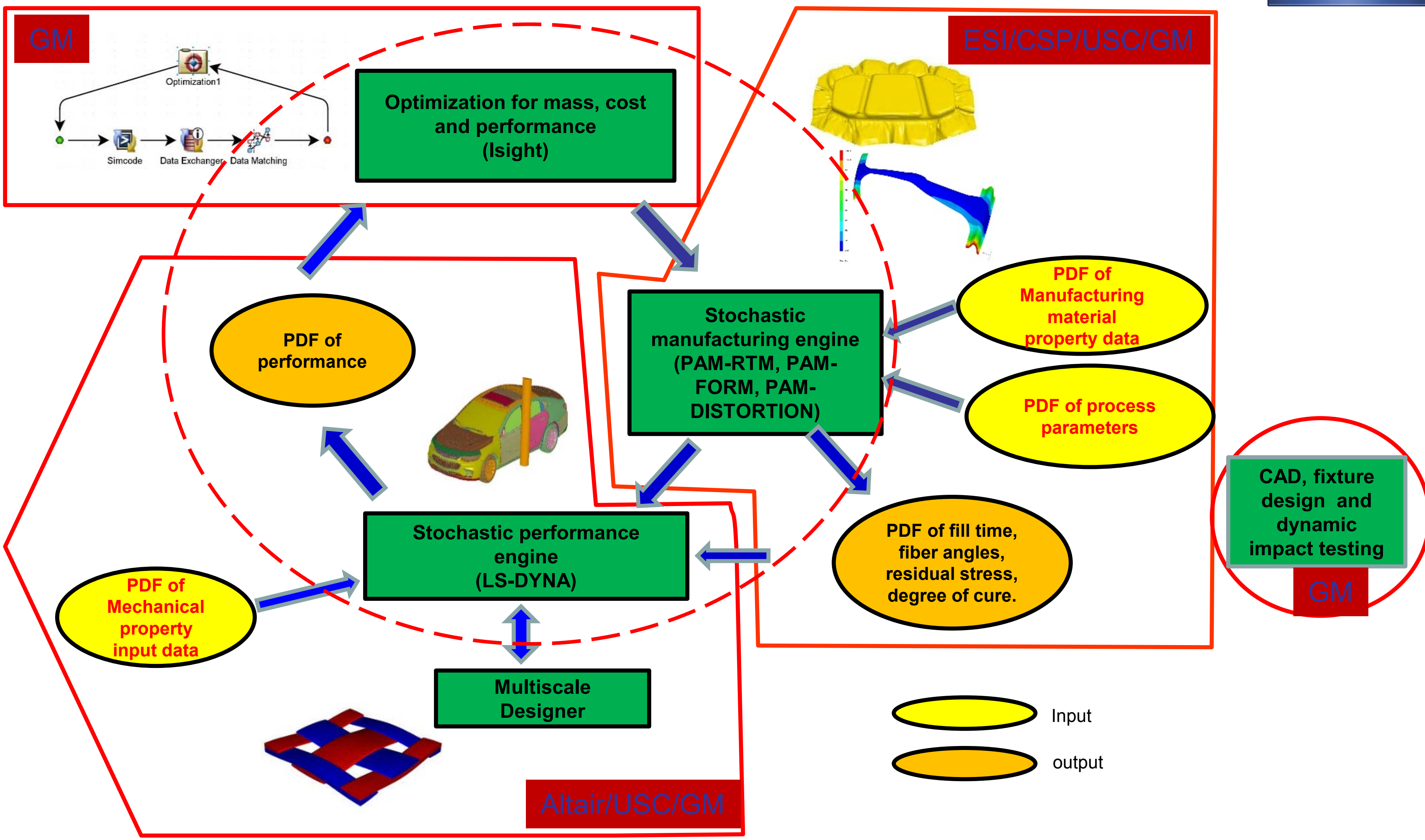
- An ICME approach to develop
  - computational methodologies and tools for predicting stochastic manufacturing.
  - computational methodologies and tools for predicting stochastic performance.
  - Integrated tools to predict the performance of an assembly.

- A team comprised of an automobile OEM, a Tier 1 composite system supplier and molder, software simulation companies in the areas of composite manufacturing and performance prediction, and a DOE funded SciDAC institute for uncertainty quantification.

- Composite System Supplier: Responsible for selecting materials and manufacturing processes for high volume manufacturing, providing plaques and coupons for generating the data required for model calibration and validation.
- Software Companies: Responsible for the development of predictive tools for manufacturing and structural performance
- Stochastic Modeling Research Group: Responsible for developing stochastic models for both manufacturing and structural performance
- OEM : Responsible for developing and conducting experiments for model confirmation, integrating the manufacturing and structural performance tools, demonstrating the technology by design, optimizing, building and testing a carbon fiber automotive assembly as well as validating the developed models by comparing the predictions with experimental results.

Approach/Strategy

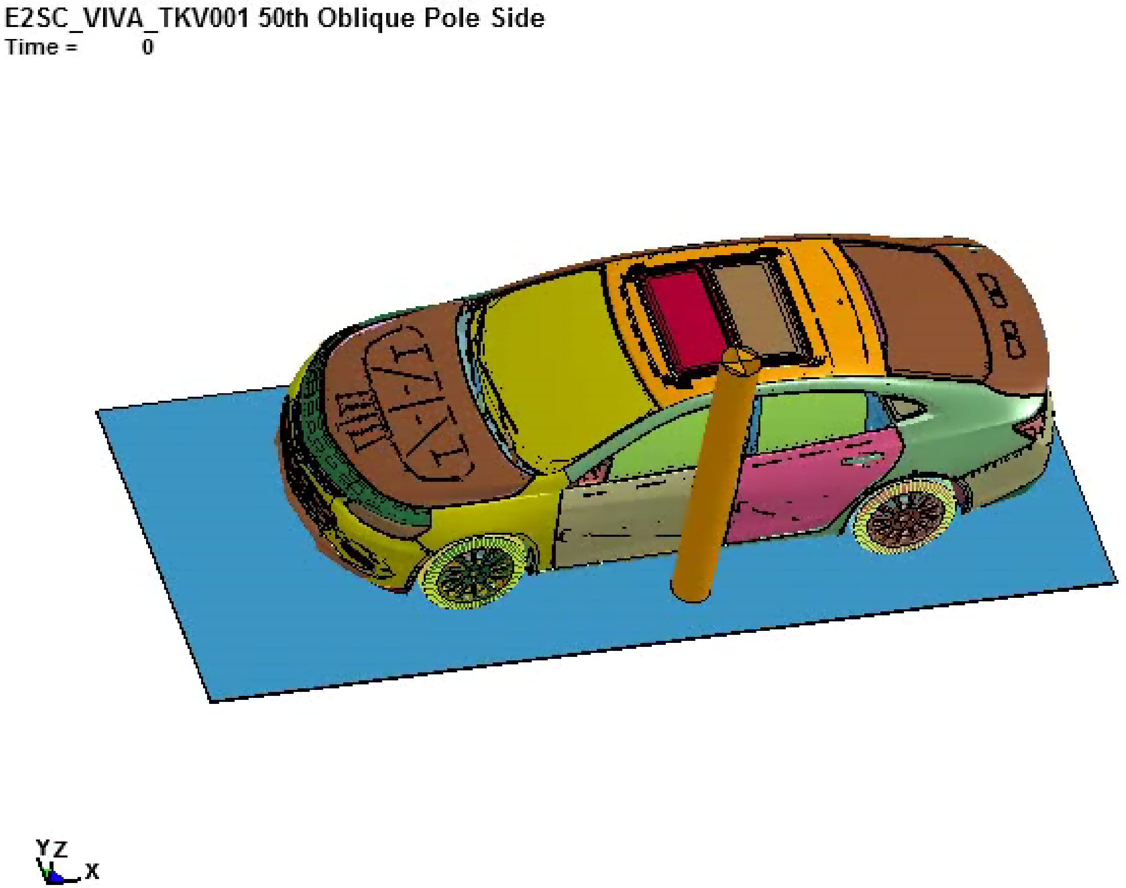
Developed a process flow of tool development



Accomplishments

FY 16 Accomplishments

- 7 Baseline assemblies were tested and the performance requirements both analytically and experimentally determined. These results will guide the design of the future carbon fiber automotive assembly.



Accomplishments

Manufacturing simulation tool development and validation

- Draping model development and validation
- C-RTM tool development and validation

Stochastic manufacturing simulation tool development

- Model variables as stochastic random variables and random fields
- Stochastic results for resin transfer molding

Structural simulation tool development and validation

- Hybrid plasticity model for the resin
- Correlations for off-axis plies
- Non-orthogonal models for woven fabrics
- Crush simulation

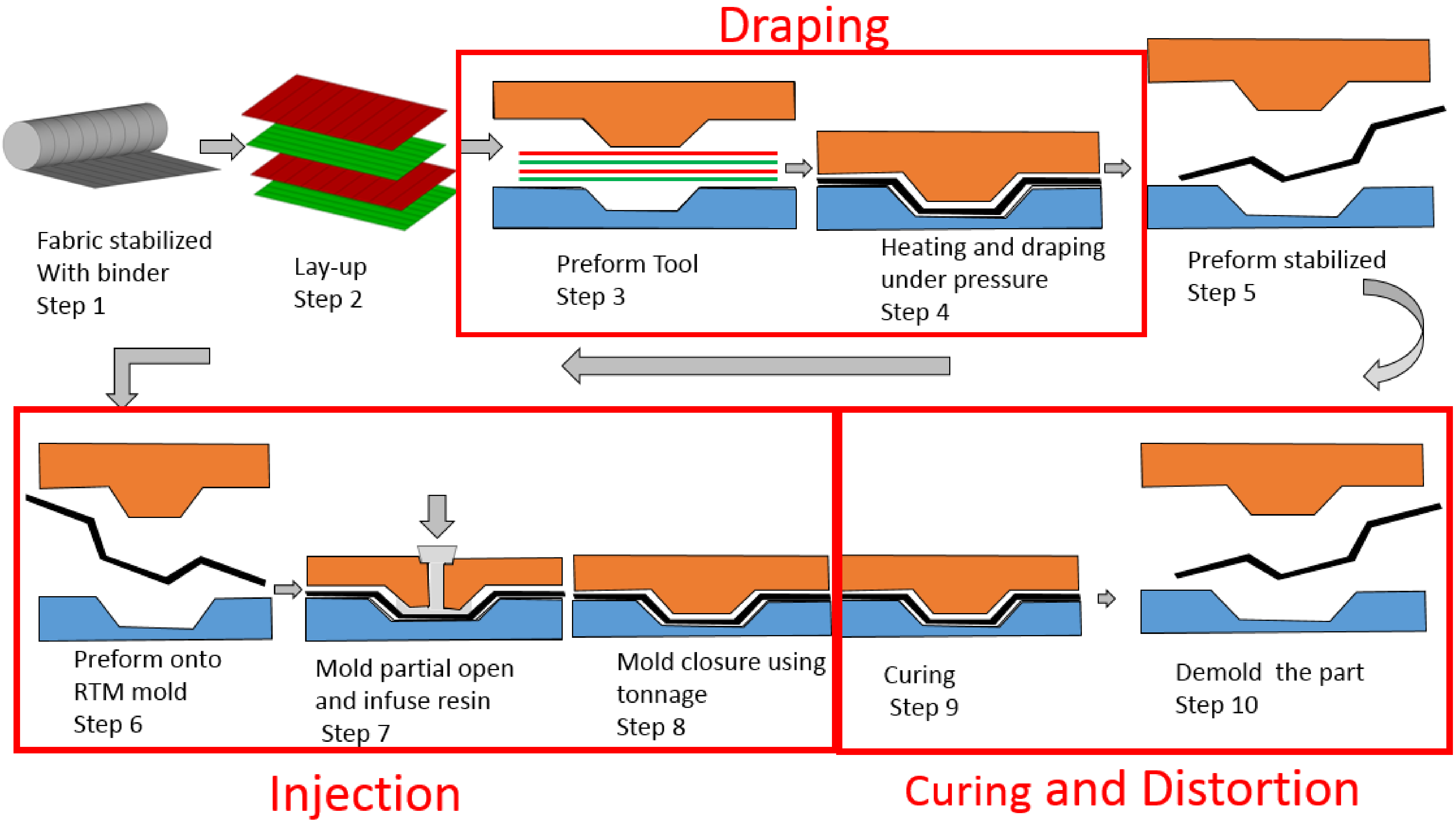
Stochastic structural simulation tool development

- Results for NCF tension test
- Results for NCF three-point bend test

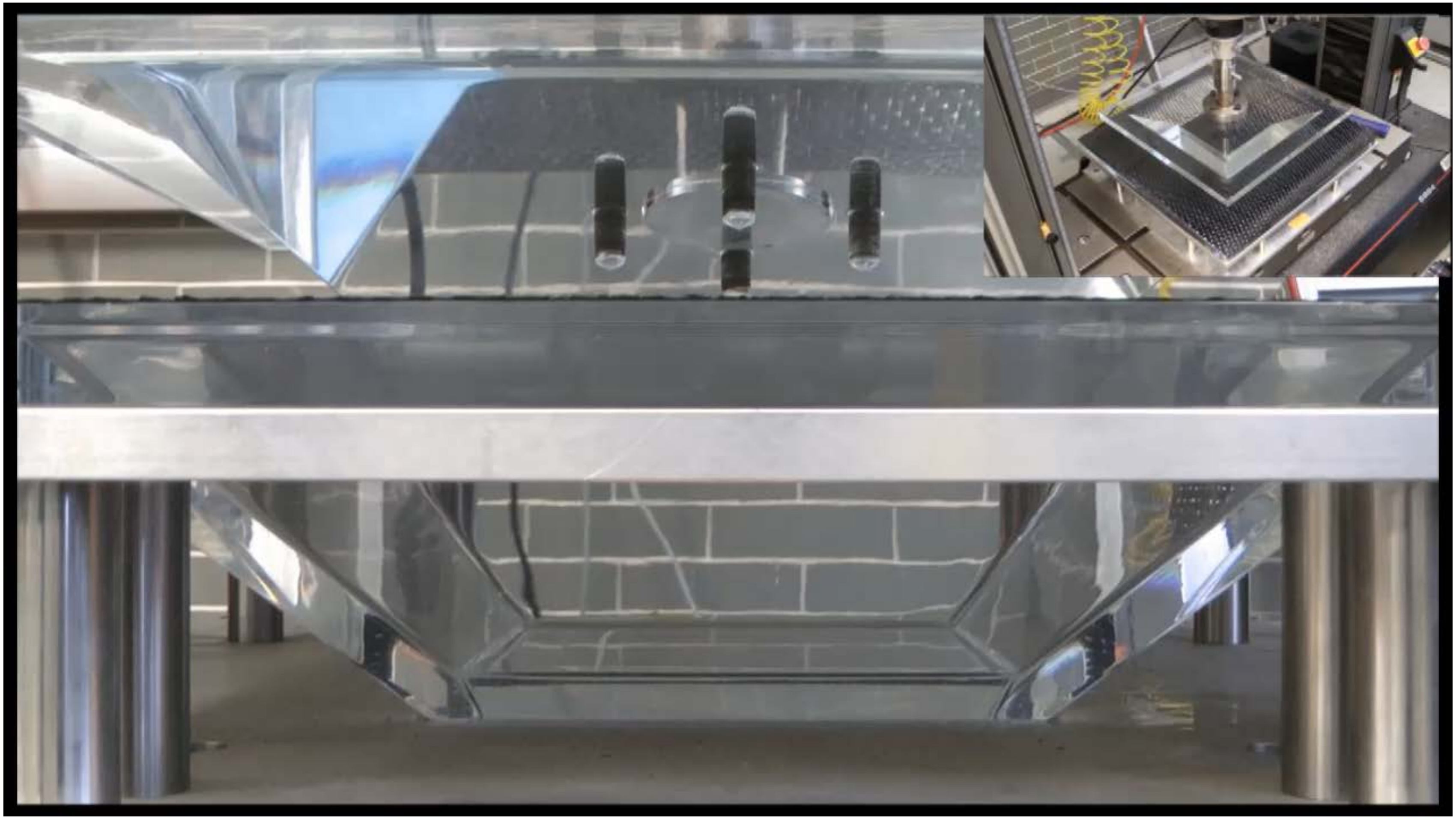
Mapping of manufacturing outcome onto structural models

Preliminary design of carbon fiber automotive assembly for high volume manufacturing

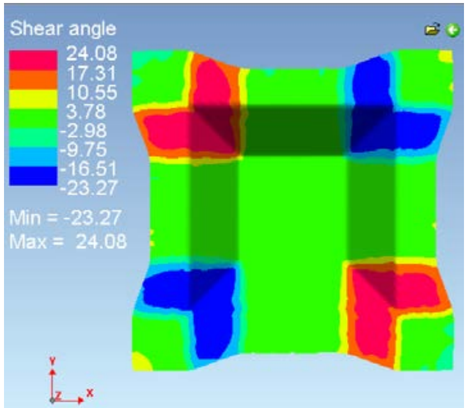
Manufacturing Process

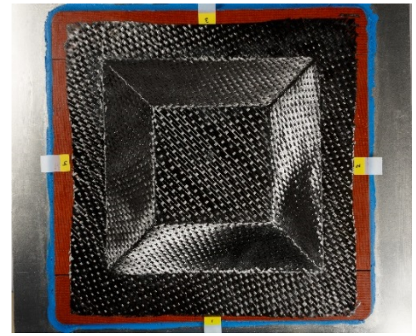


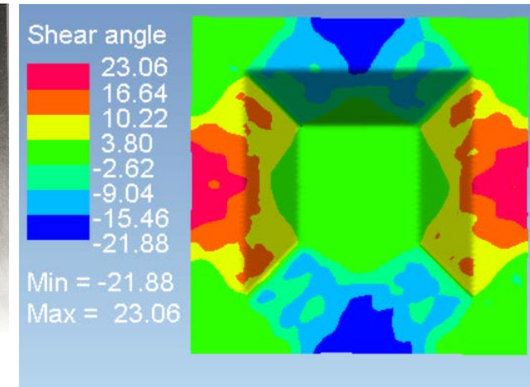
Deformation Experiment



Draping Summary

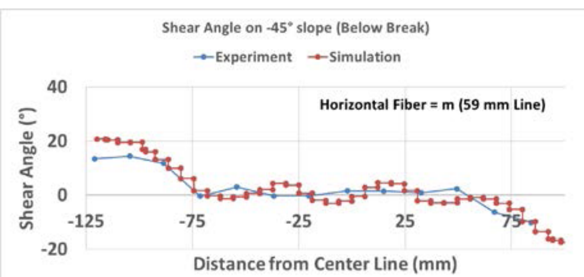


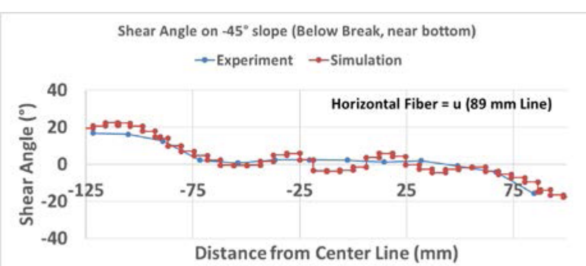




(0/90)

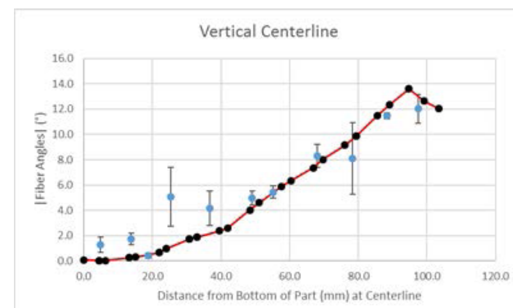
(45/-45)

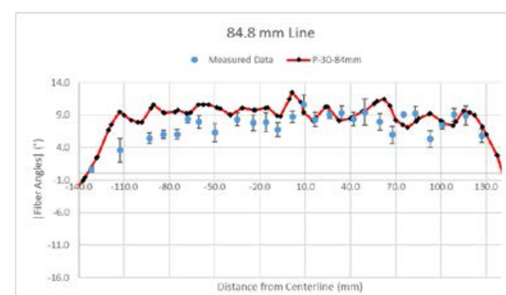




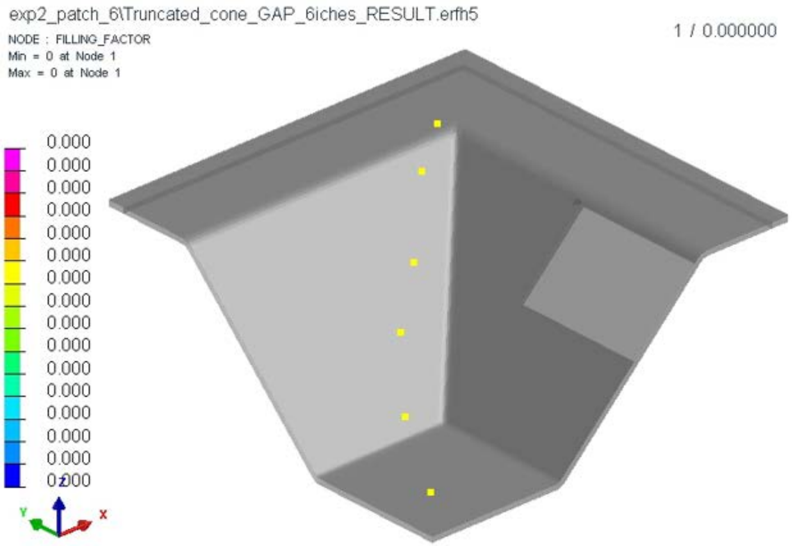
- **Draping studies carried out on both:**
  - **5 Harness Satin Fabric**
  - **2 x 2 Twill Fabric**
- **Global orientations**
  - **0°/90°**
  - **+/- 45°**

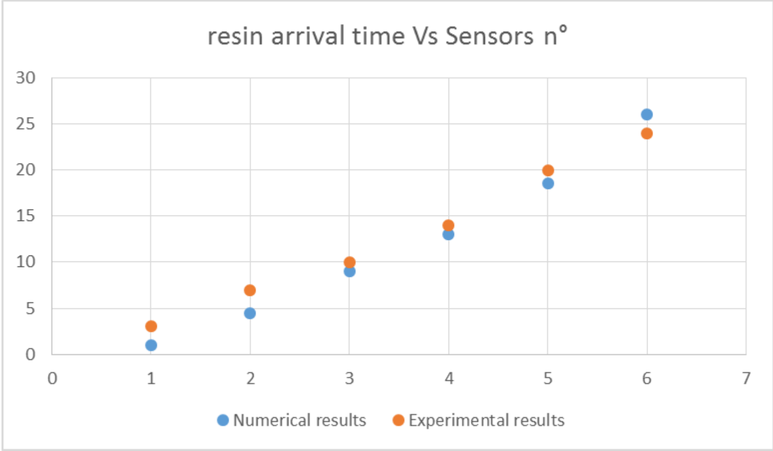
- **Excellent correlations between simulations and experiments for all conditions**

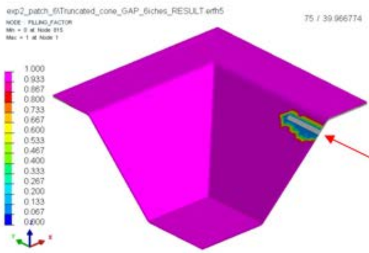




C-RTM Results

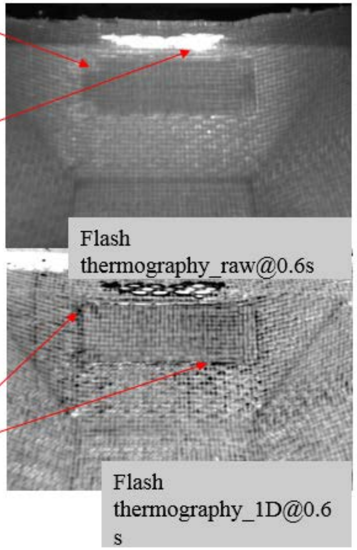


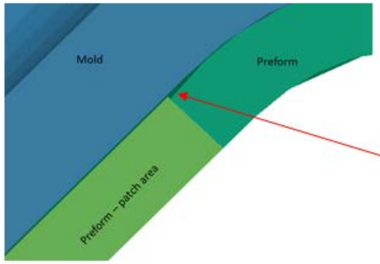




Patch 6 inches

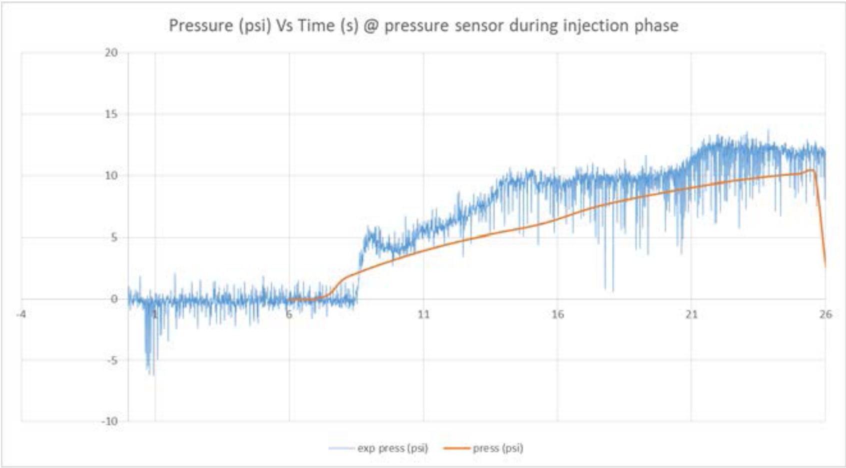
Void/Dry fabric





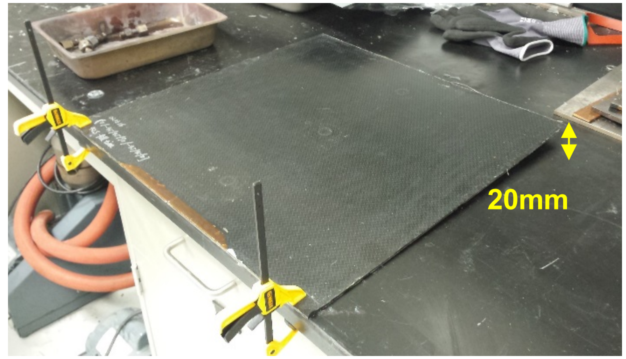
- Through solid mechanics, the final deformed shape highlights the channel

Resin channels

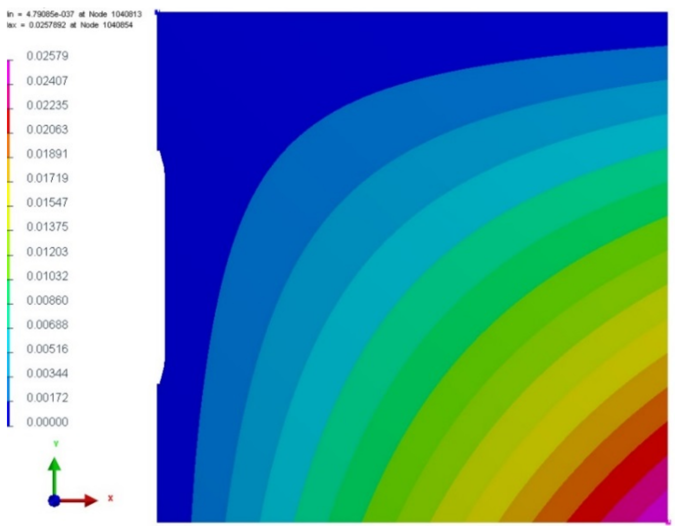


PAM-Distortion Analysis

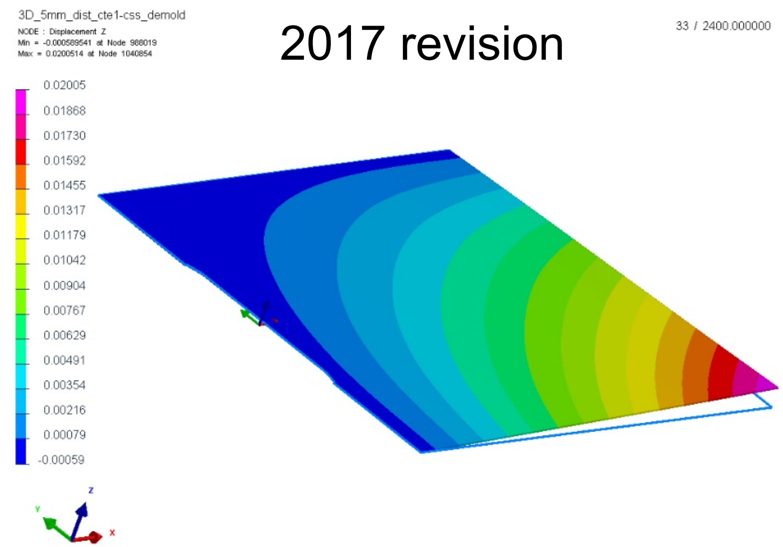
- Unsymmetrical layup : 0/45/-45/90/90/45/-45/0



Old version



2017 revision



Geometric linearity ($\epsilon_x = \frac{\partial u}{\partial X}$)

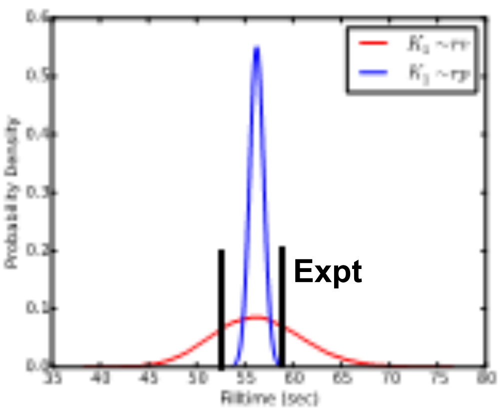
Geometric nonlinearity

$$(\epsilon_X = \frac{\partial u}{\partial X} + \frac{1}{2}\left(\left(\frac{\partial u}{\partial X}\right)^2 + \left(\frac{\partial v}{\partial X}\right)^2 + \left(\frac{\partial w}{\partial X}\right)^2\right))$$

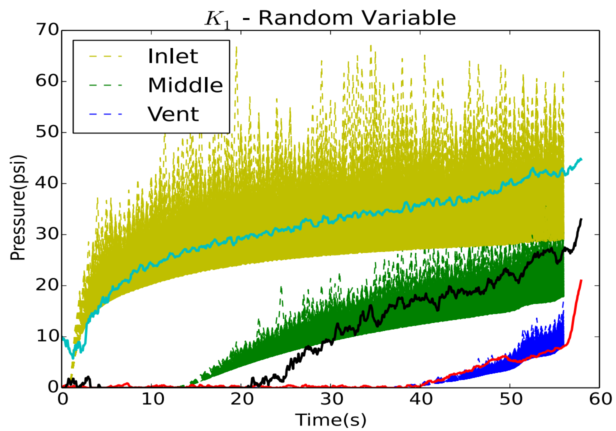
Distortion - 25.8 mm

Distortion - 20.1 mm

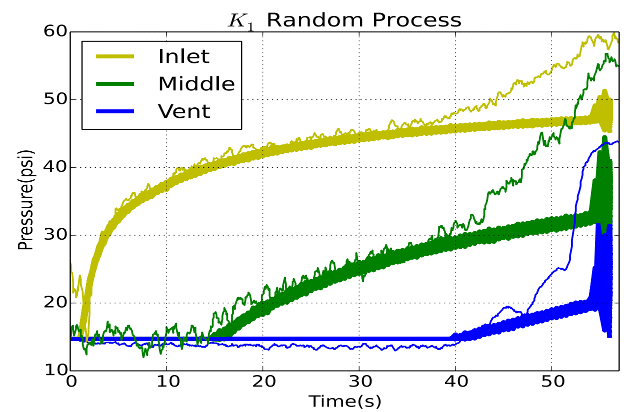
Stochastic manufacturing process



PDF of fill time: Random variable vs. random process and Experiments



Pressure vs. Time Permeability as random variable



Permeability as random process in 100 dimensions.

Basis adaptation of PCE was critical for reducing the 100 dimensions to 3 dimensions.

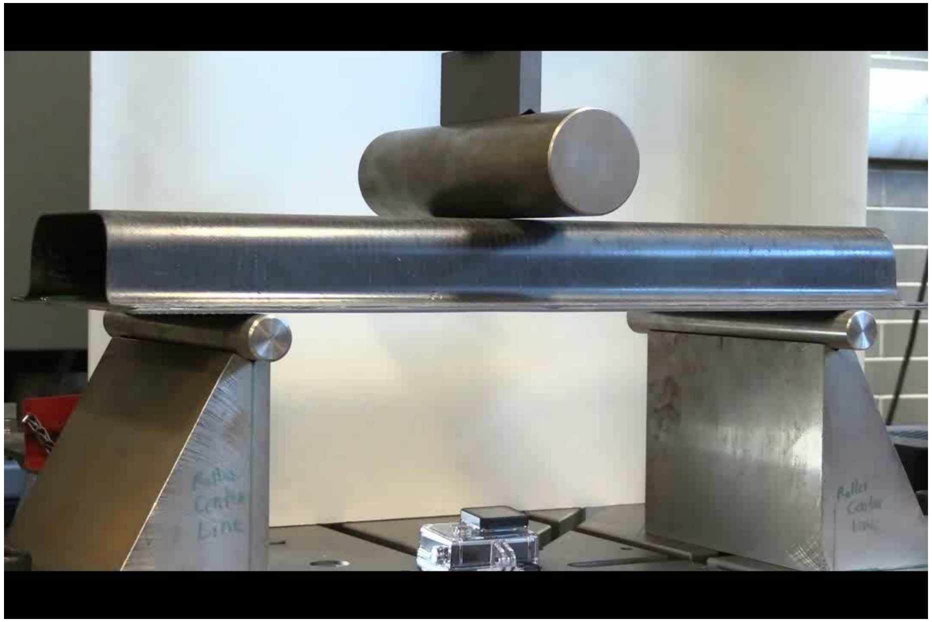
Structural Modeling – Goals/Accomplishments

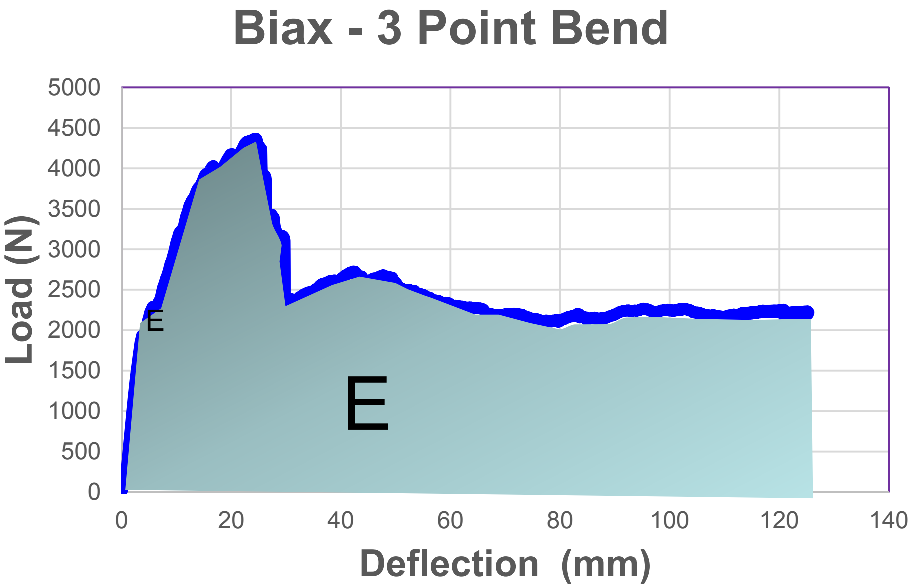
- Multiscale Designer Framework
- Parametric unit cells
- Simultaneous calibration with multiple experiments
- Math models calibrated and validated for NCF, woven and chopped material systems

All these developments are incorporated into Multiscale Designer software within HyperWorks and will be available for commercial use.

Quasi-static 3-point Bend Test

Biax





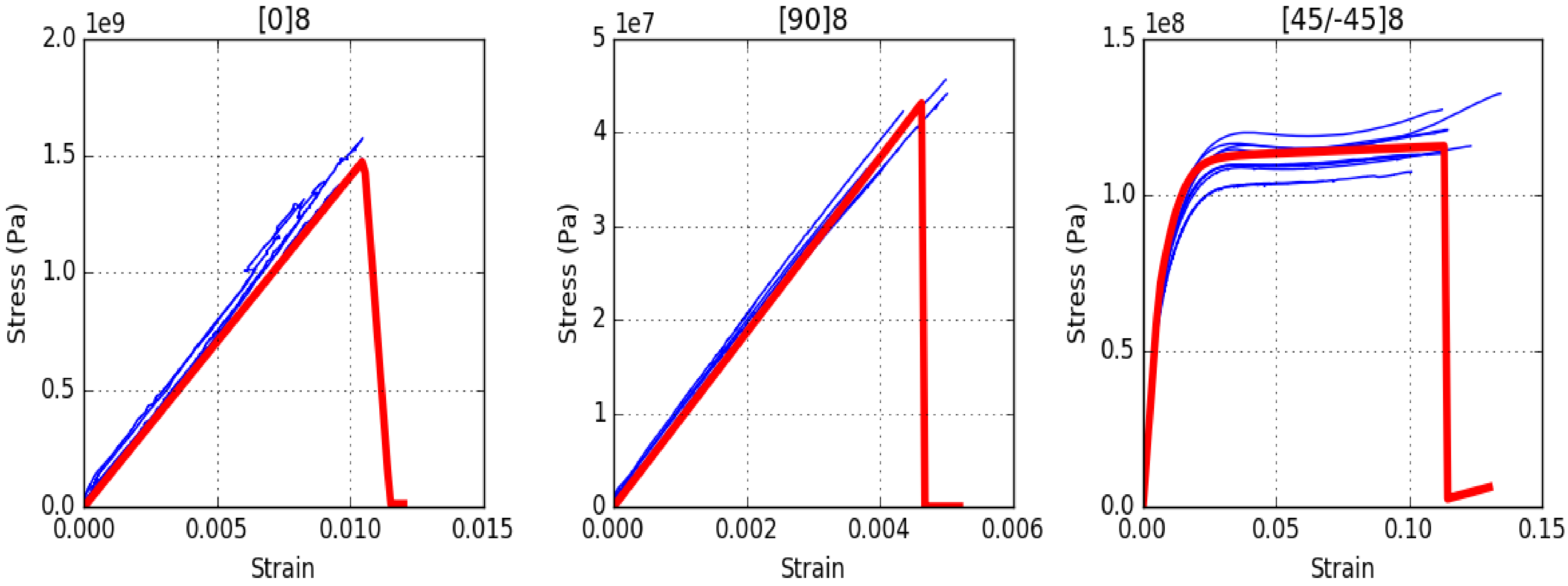
Off-axis plies show significant ductility and they are of significant interest for energy absorbing applications. It is important to ensure that computational models are predictive for these lay-ups.

Structural Performance Model

Developed a hybrid plastic material model for the resin

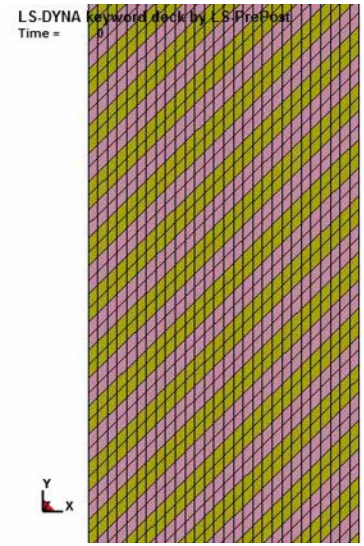
- plasticity and isotropic damage driven by volumetric strain
  - Brittle failure when ε_{kk} exceeds a critical value
  - No softening due to plastic deformation and no plastic damage mechanism

$$\sigma_{ij} = (1 - w)L_{ijkl}(\varepsilon_{kl} - \varepsilon^{p}_{kl})$$

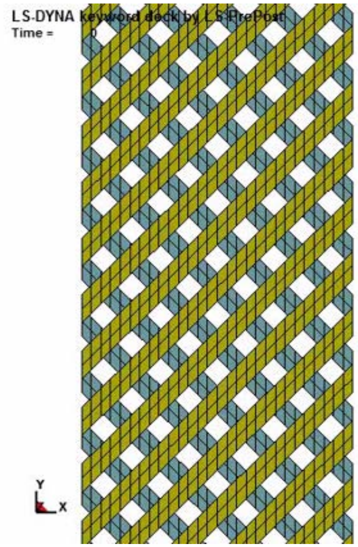


Meso-scale Modeling

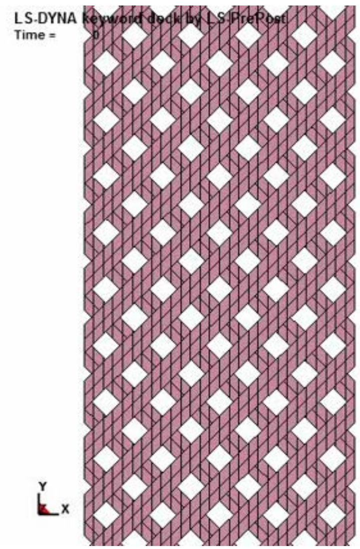
Explicit modeling of tows and resin at the meso-level



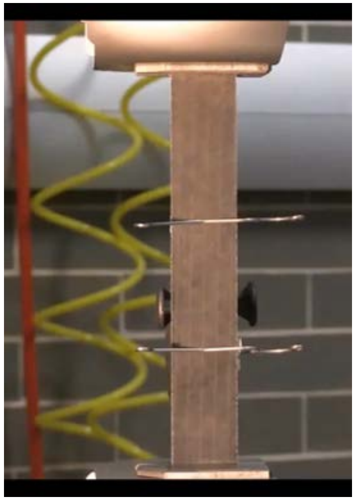
NCF composite



Tows



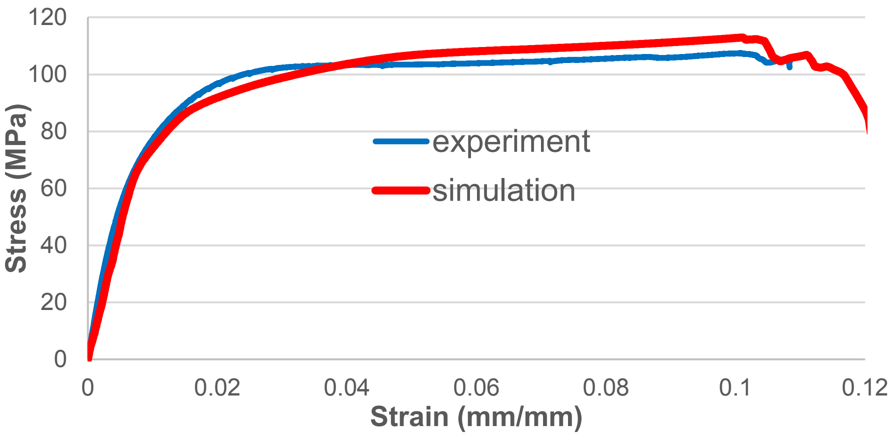
Resin



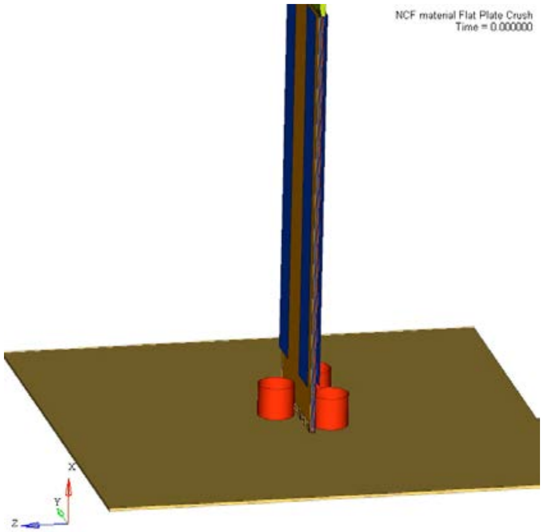
Experiment

Elasto-plastic material model for resin
Progressive failure material model for tows

Excellent correlations



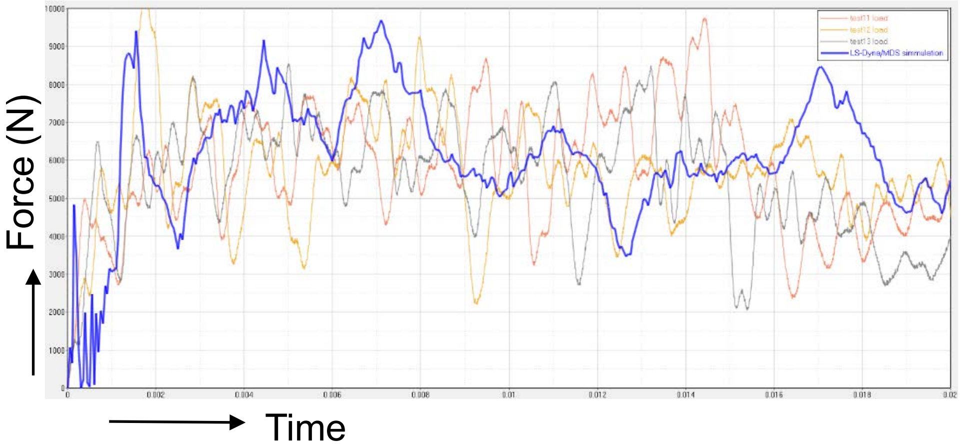
Crush Simulation

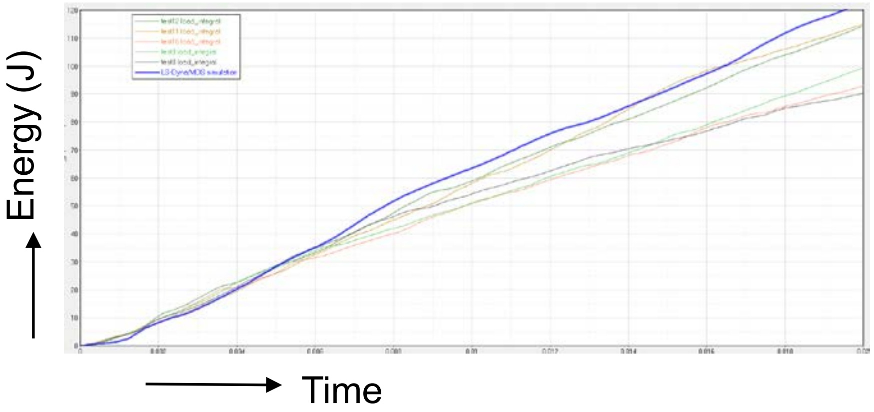


Simulation

Experiment

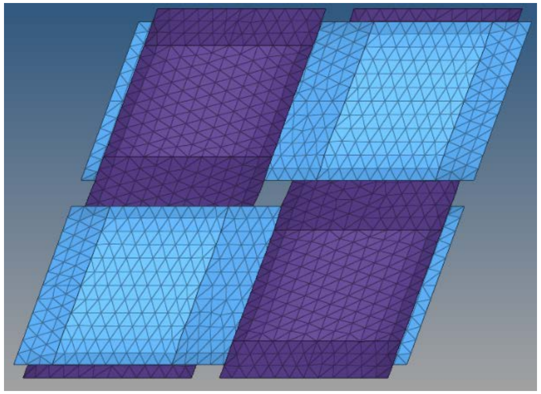
Simulation

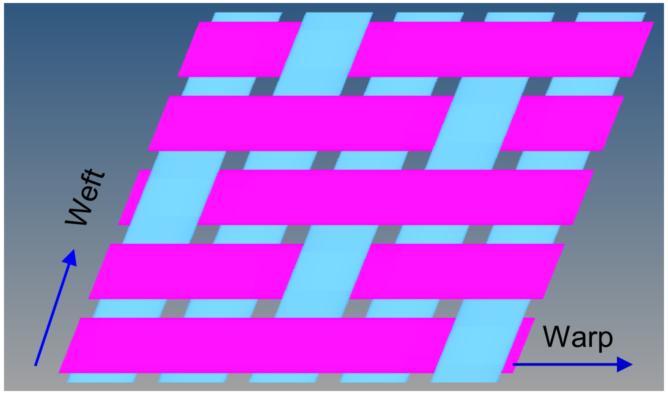


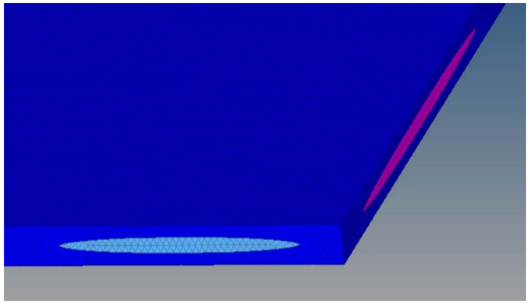


Simulation was predictive in correlating with load versus time and crush morphology

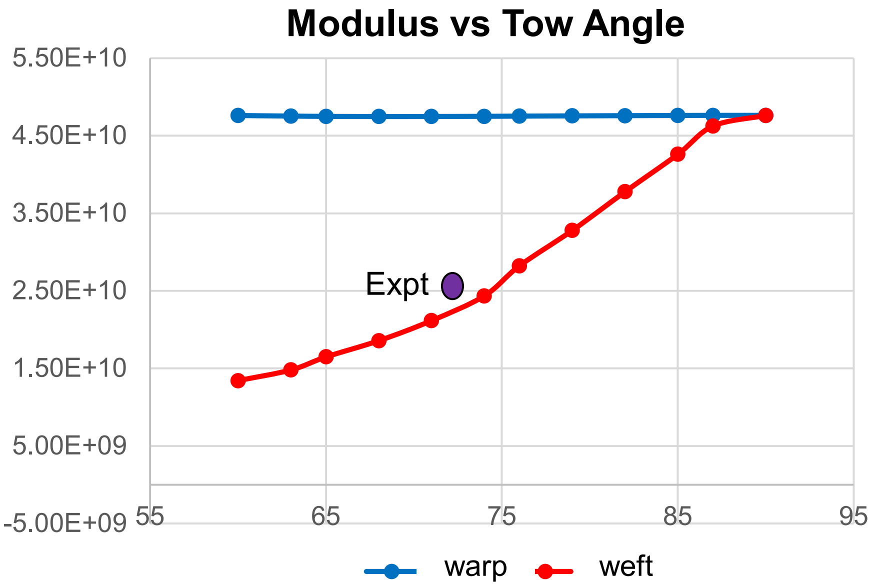
Modeling of Non-Orthogonal Weave

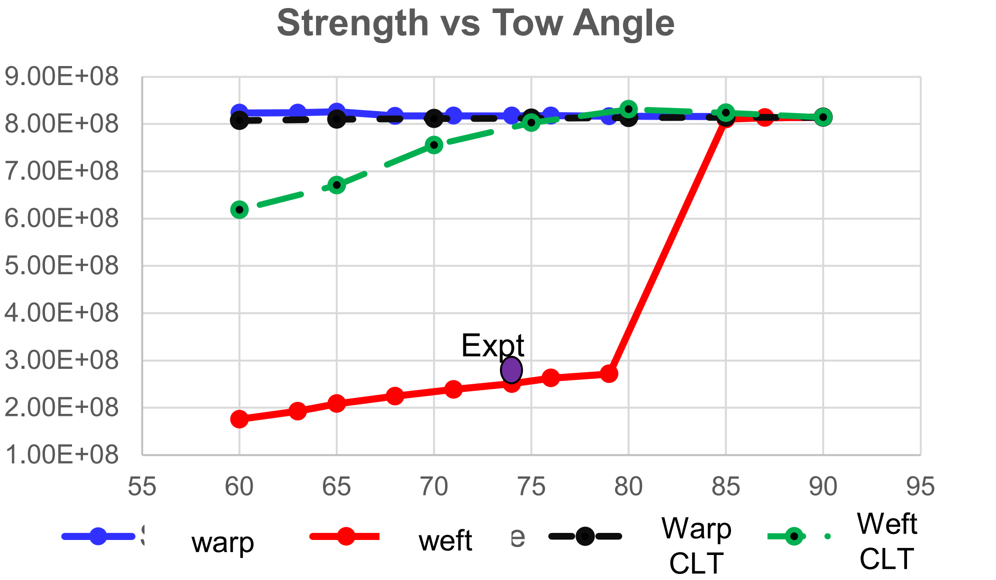






Unit cell of non-orthogonal weave was created by shearing the orthogonal mesh using HyperMorph – very novel approach to account shearing in multi-scale framework





Mapping

ESI – Output in HDF5 format

↓

Altair- HDF5 Reader

↓

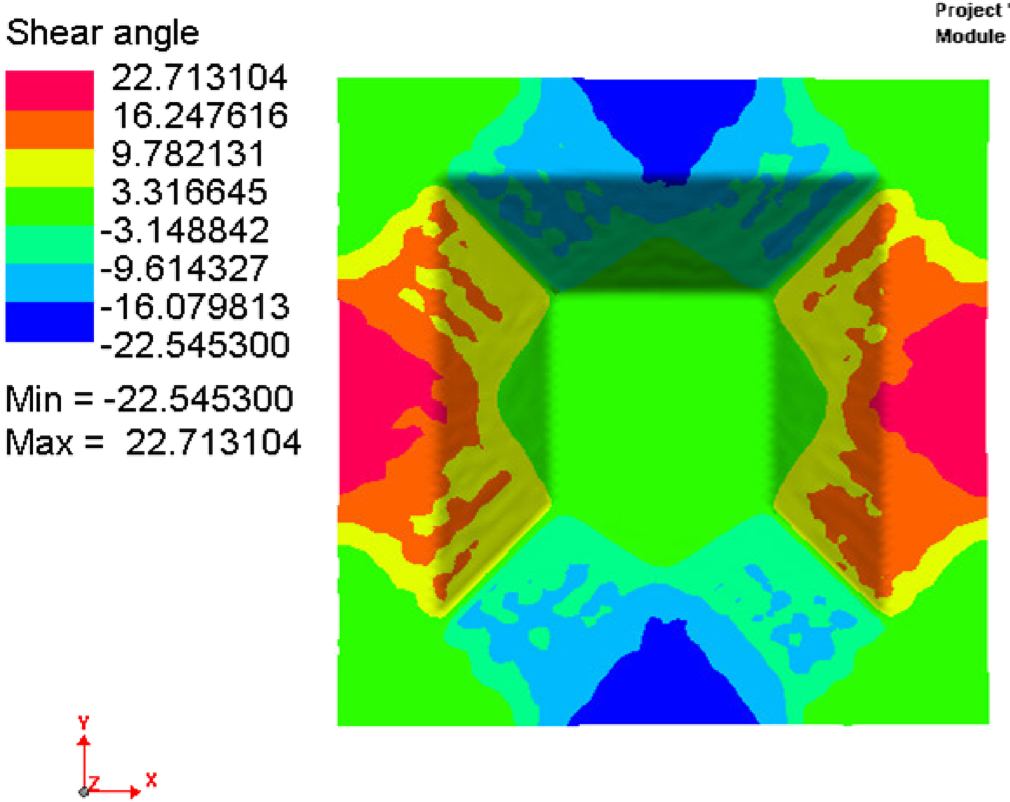
Hypermesh Composite Database captures the data

↓

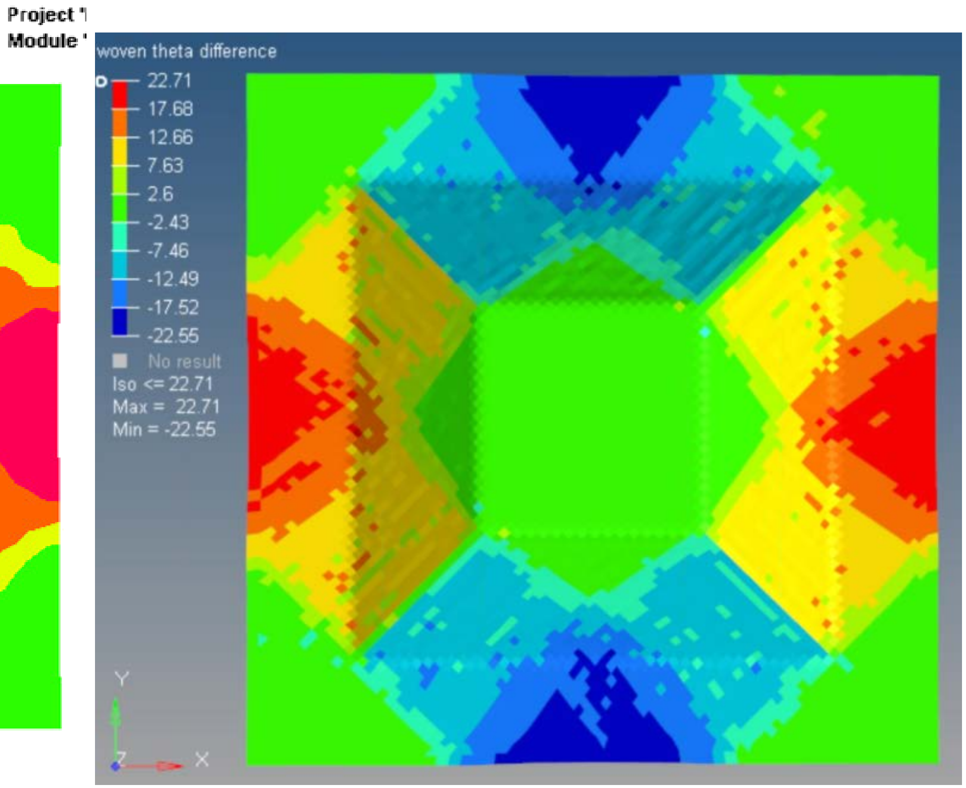
Hypermesh maps the quantity of interest to different mesh density used for structural models

- Industry first: a robust mapping software in the framework of commercial software was developed to map the manufacturing outcome onto structural models for structural composite materials.
- Angle changes and residual stresses are mapped.

Shear Angles

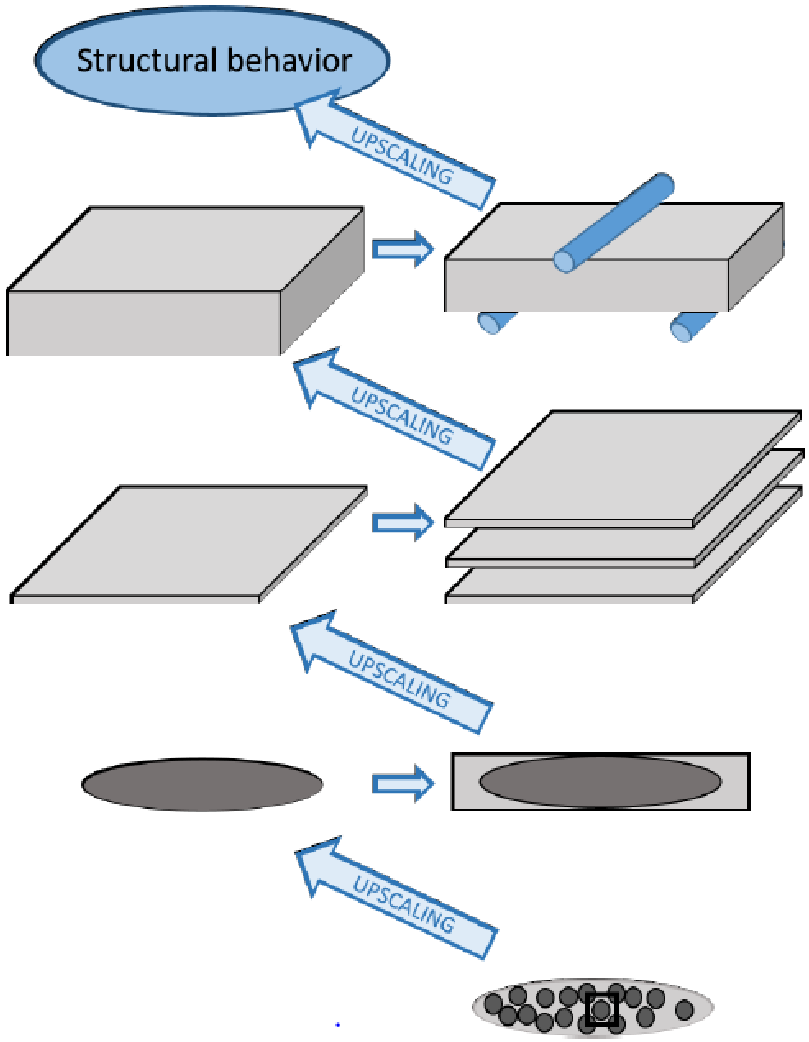


Shear angles as predicted from ESI- PAMFORM



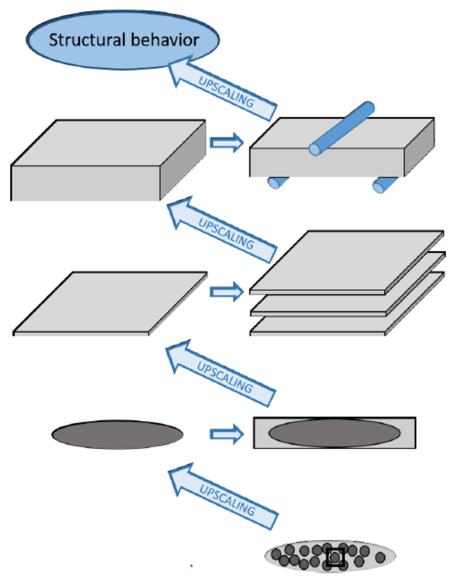
Shear angles after mapping into Altair-Hypermesh

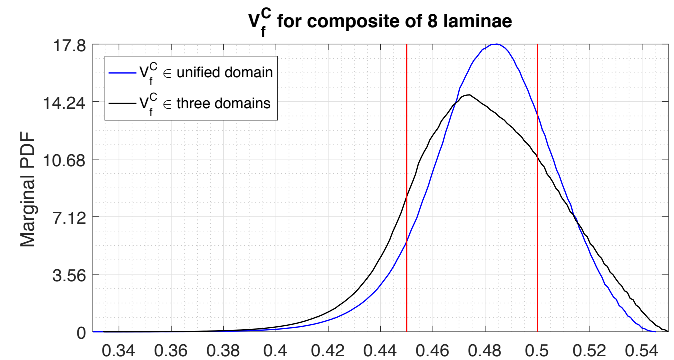
Stochastic Structural Simulation

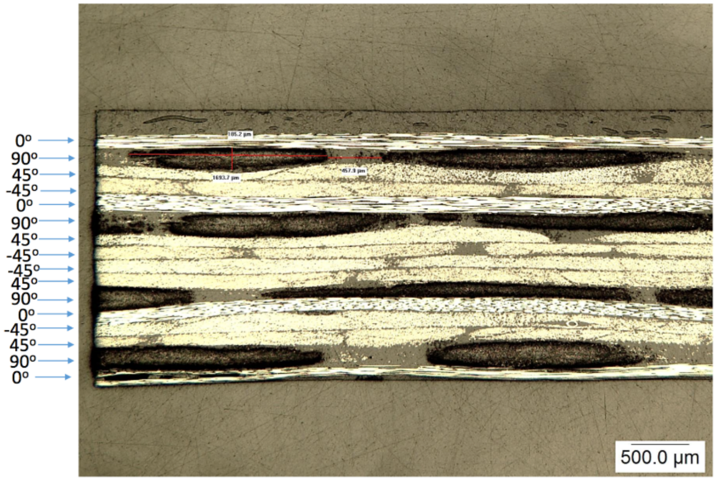


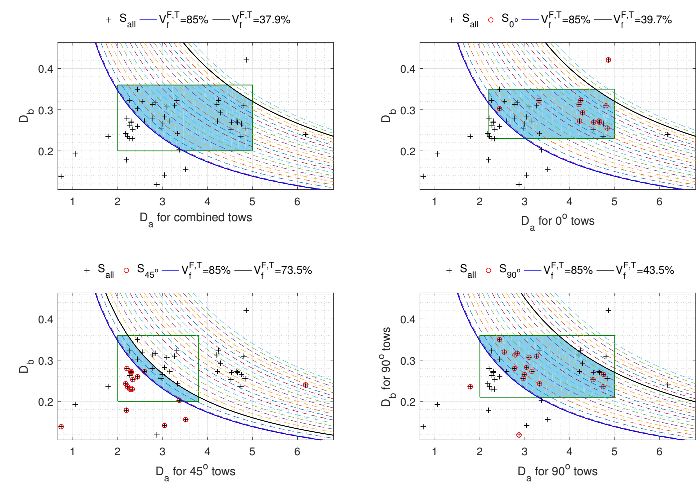
Framework

Stochastic Structural Simulation

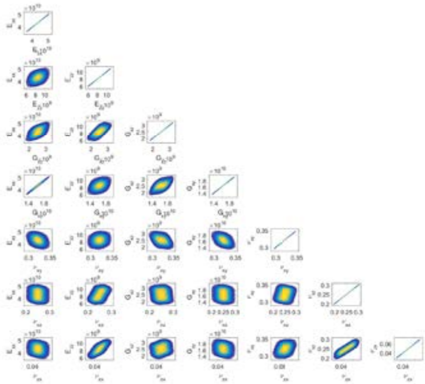


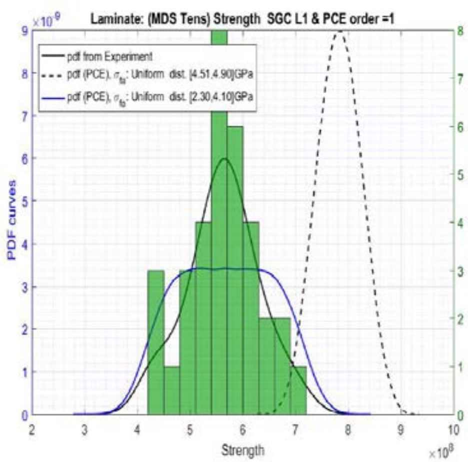


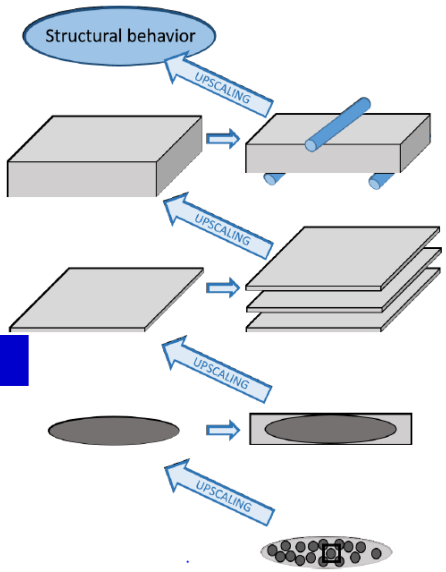


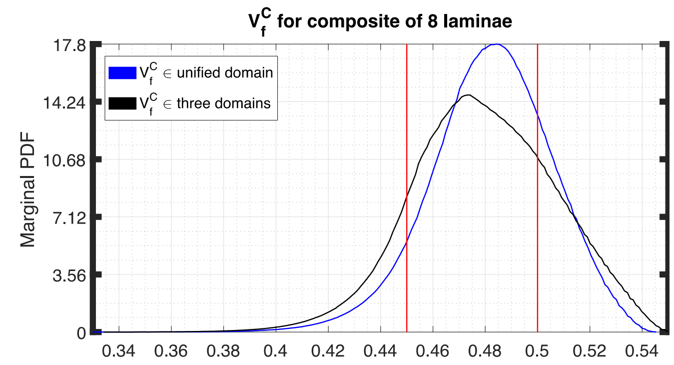


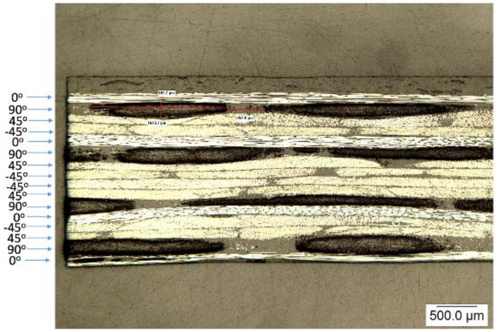
Stochastic Structural Simulation

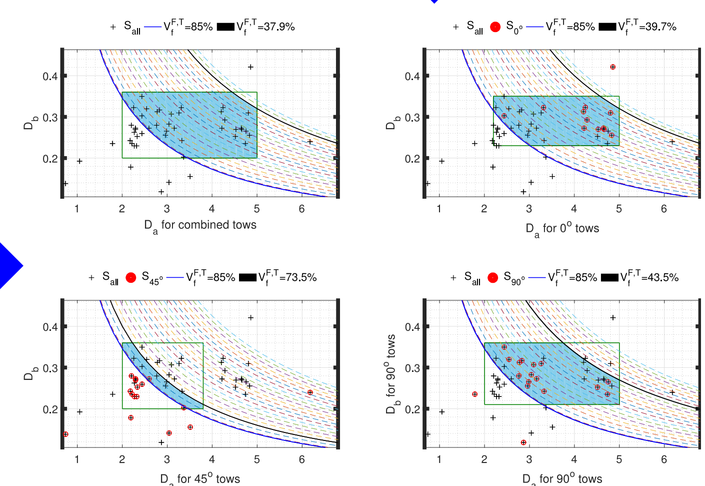












Responses to Previous Year Reviewers' Comments

1. The reviewer said that the approach is a bit vague and the overall scope is overly optimistic. Characterizing material models, evaluating process simulation and structural performance for a full suite of thermosets, thermoplastics, chopped-, uni-, and woven composites, were described as lofty goals by this reviewer. The reviewer added that the project seems too ambitious to be completed by 2019, particularly with one goal being to account for uncertainty across scales. The reviewer commented that the process flow of tool development needs to be refined to more clearly show the process steps.

Answer: We believe that the study we undertook regarding the material characterization of different material systems is essential and adds greater value to the project. The carbon fiber automotive assembly we are working on requires different material systems to optimize mass and cost. The multi-scale framework we are developing takes into account these different microstructures easily and systematically without adding extra work.

2. The reviewer said that a good balance of collaborators exist, with one OEM, a Tier 2 supplier, modeling companies, and a university, but suggested that the project should consider material suppliers. This reviewer is interested in the pre-competitive research that will be generated in order to benefit the industry.

Answer: This is a good suggestion. Given the scope of our project dealing with different carbon fiber and resin material systems, we felt that if we included a single material supplier, we would not get access to other material systems in the market place. We believe that our Tier 1 supplier will be able to access several material suppliers at the same time.

Responses to Previous Year Reviewers' Comments

3. The reviewer would like to see the project include chopped CF thermoplastic prepreg or three-dimensional (3D) preform materials. This is a lower cost approach than resin transfer molding (RTM)/thermoset. In overview, the reviewer would like to see more thermoplastic in the project based on recycling, cycle time, and more simplistic chemistry than thermosets.

Answer: We have included thermoplastics in our project from beginning.

4. The reviewer said yes, but RTM with thermoset chemistry has not been demonstrated as a cost-effective high volume process. The European OEMs who typically lead this type of advanced technology development seemed to have dropped this as a prime path. The reviewer suggested including a high-temperature thermoplastic, such as PPA

Answer: There is significant progress in the usage of HP-RTM equipment with fast curing resin systems to achieve higher through-put. In this aspect, the reviewer is correct that US is lagging behind Europe. This project is scoped to bring the technology base to the US. HP-RTM is a process being studied in our project which can be used to build components for automotive assembly systems.

Partners/Collaborators

General Motors - Prime	Overall project management, execution, baseline performance evaluation, material data generation for manufacturing and structural simulations, assembly of the CF automotive assembly, testing and validation. material database creation for manufacturing and structural simulation, integrate the manufacturing and structural models, develop cost models, demonstrate the technology development.
Continental Structural Plastics (CSP)	Technology supplier, molder - coupons, plaques and components, develop design for manufacturing guidelines, input for cost models.
ESI Group, NA	Manufacturing simulation models for the manufacturing processes chosen in the project.
Altair	Multi-scale simulation models for the structural performance in the LS-DYNA, ABAQUS and Radioss framework.
University of Southern California	Develop stochastic drivers that work for manufacturing and structural performance simulations. Able to utilize the previous work done on a DOE supported work on uncertainty quantification (SciDAC institute).

Remaining Challenges and Barriers

- Design and optimize the automotive assembly in a virtual environment to meet the same performance targets as the baseline. The mass and cost savings need to meet, and if possible exceed DOE targets.

- Develop methods in optimization, stochastic simulations to allow simulations run in a reasonable time.

Proposed Future Work

FY 2017

- Develop cost models for high volume manufacturing processes.
- Develop high volume manufacturing designs for the automotive assembly.
- Design, optimize the automotive assembly virtually.

FY 2018

- Build the tooling required to manufacture the automotive assembly
- Fabricate components and assemble them to test under crash sled.

Any proposed future work is subject to change based on funding levels.

Summary

- A Manufacturing simulation tool was validated by successfully correlating experiments for draping and compression resin transfer molding.
- A new hybrid plasticity model for the resin inside the unit cell was developed. Predicted results correlated very well with experiments using off-axis plies.
- A novel unit cell model for non-orthogonal weaves was developed and this development works well with the existing multi-scale framework.
- A mapping procedure was developed in the framework of a commercial software such that the manufacturing outcome was accurately mapped onto structural models.

Technical Back-Up Slides

Governing Equations in Injection, Curing and Warpage

Filling – Stage – Coupled flow, heat and cure

Darcy's equation – Fluid Flow $\nabla \cdot (-\frac{K}{\mu}\overrightarrow{\nabla P}) = 0$

Heat Transfer Equation $\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr} V \cdot \nabla T = \nabla \cdot (k \cdot \nabla T) - \rho_r \, \Delta h \, \frac{d\alpha}{dt}$

Curing Kinetics $\frac{d\alpha}{dt} = \left(A_1 \exp\left(-\frac{E_1}{T}\right) + A_2 \exp\left(-\frac{E_2}{T}\right) \cdot \alpha^m\right) \cdot (B - \alpha)^n$

Curing – Stage – Coupled heat and cure

Heat Transfer Equation $\rho C_p \frac{\partial T}{\partial t} + \rho_r C_{pr} V \cdot \nabla T = \nabla \cdot (k \cdot \nabla T) - \rho_r \, \Delta h \, \frac{d\alpha}{dt}$

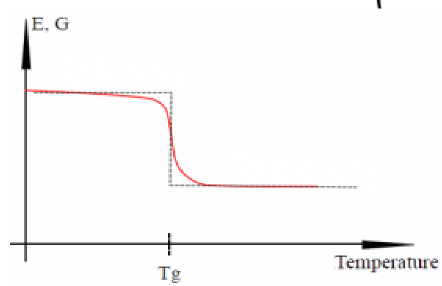
Curing Kinetics $\frac{d\alpha}{dt} = \left(A_1 \exp\left(-\frac{E_1}{T}\right) + A_2 \exp\left(-\frac{E_2}{T}\right) \cdot \alpha^m\right) \cdot (B - \alpha)^n$

Distortion- Stage (Thermo- Chemical Mechanical Analysis)

$$\sigma_{ij}(t) = \int_0^t C_{ijkl}\big(\xi(t) - \xi(\tau)\big) \frac{\partial\left(\epsilon_{kl} - \epsilon_{kl}^E\right)}{\partial \tau} d\tau \qquad C_{ijkl}(t) = \begin{cases} 0 & , X < X_{gel} \\ C_{ijkl}^{\infty} + \sum_{p=1}^{P} C_{ijkl}^{p} \cdot \left(e^{-t/\rho_{ijkl}^{p}}\right), X \geq X_{gel} & , no \ sum \ on \ i, j, k, \end{cases}$$

Di Benedetto function → T_g

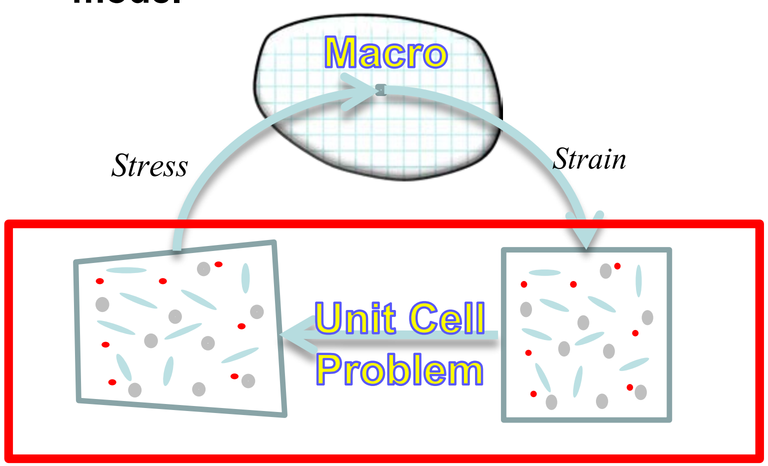
$$\frac{T_g - T_{g0}}{T_{g\infty} - T_{g0}} = \frac{\lambda X}{1 - (1 - \lambda) X}$$



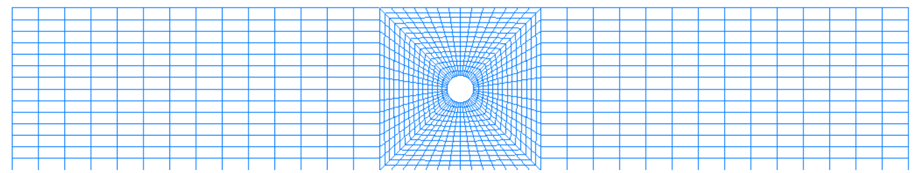
Multiscale Designer Capabilities

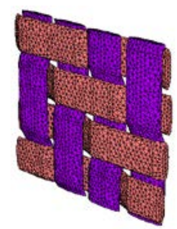
1. Parametric RVE definition
   1) Geometric scripts
   2) User-defined parametric RVE
   3) Integration with experimental data

2. Computational Efficiency: **Speed comparable to single scale model**



3. Size Effect & Softening after Damage





Challenges:
(1) Unit cell size comparable to the hole size and much bigger than macro-element size
(2) Strain softening due to damage

An attempt to account for size effect and softening due to damage

Remedies:
(1) Rescaling of damage models and
(2) Staggered nonlocal multiscale approach